

# Digital High Density (80 Mb/s) Tape

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*This article describes work with a state-of-the-art high density digital PCM tape recorder-reproducer system recently purchased by JPL. The tape recorder is designed for 80 Mb/s operation at an overall bit error rate of  $10^{-5}$  and for 40 Mb/s operation at  $10^{-6}$ . The article describes the process of measuring the error rate. Also detailed is a data rate buffer designed for use in recent radar experiments and generalizable to most potential uses of the recorder system.*

## I. Tape Transport

Nothing is more crucial to the performance of a high density tape recording system than the tape transport. In standard computer applications, the transport is taken for granted, but in this system with narrower tracks on wider tape moving faster than computer tape recorders, the transport is critically important.

Each data track is 0.635 mm (0.025 in.) wide with 0.254-mm (0.010-in.) spacing between tracks. Tape speed is 152 or 305 cm/s (60 or 120 ips). The system data rate using all 28 tracks is 86.8 Mb/s (Megabits per second) at 305 cm/s (120 ips) and 43.4 Mb/s at 152 cm/s (60 ips). Omitting the two edge tracks (which have a higher error rate than the inside tracks) the data rate is 80.6 Mb/s at 305 cm/s (120 ips) and 40.3 Mb/s at 152 cm/s (60 ips). The tape is 25 mm wide and the transport can accept reels up to 38 cm in diameter. A 38-cm reel holds about 3300 meters of 25-micron-thick tape.

Tape tension is maintained with tension arms whose position errors are fed back to the reel hub motors. Tape motion is controlled by a capstan-and-pinch roller system. Tape speed is controlled by a servo which phase locks the

capstan tachometer signal (derived from a rotating patterned wheel and an optical sensor mounted on the capstan motor shaft) to a crystal reference.

All the tape guides are mounted on roller bearings. Both tape guides and reel hubs are mounted on platforms with small jackscrews so that they may be aligned.

Alignment of the guides and hubs is very critical because the guides provide no restoring force to keep the tape centered in the tape path. Strict parallelism must be maintained between the axes of all the rotating elements (hubs and guides) and the axis of the capstan. If parallelism is not maintained, the two edges of the tape are subjected to different tensions resulting in scalloping of one edge of the tape.

The restoring force problem is very important to this system because of the narrowness of the tracks. With tracks only 0.635 mm wide, separated by 0.254 mm, it only takes 0.127 or 0.254 mm of sideways motion to cause a 6-dB loss of signal amplitude and the resultant increase in error rate. Excessive skew can raise the system error rate by a factor of 10 to 100.

The record and reproduce heads are IRIG standard interleaved 28-track two-section heads. The odd numbered tracks are on one set of heads and the even numbered tracks on another. An earlier version of the transport with single in-line heads was found to be unacceptable, because the track widths were reduced to 0.318 mm due to problems in making a 28-track in-line head.

## II. Data Electronics (Fig. 1)

User data is delivered to the recorder at 3.1 MHz when operating at 305 cm/s (120 ips) or 1.6 MHz when operating at 152 cm/s (60 ips) on 30 differentially driven twisted pairs; 28 data lines and two clock lines. The recorded data is blocked into 512 bit blocks made up of 496 bits of user data plus 15 bits of synchronization character plus one bit of parity. Room for the 16 overhead bits is made by increasing the clock rate internally by a factor of 32/31 using a PLL. Overhead represents about 3.1% of all data actually on tape.

The data, now at a clock frequency of  $(\frac{3.2}{1.6})$  MHz is mixed with a PN sequence of period  $2^{17} - 1$ . The purpose of this is to eliminate the DC component of the user's data.

This data stream is now converted to NRZ-M and is amplified and sent to the record heads. Recording is done without any added bias signal.

On playback the signal from the reproduce heads goes through several stages of amplification, filtering, and a limiter to recover a binary signal. In this scheme the data clock is not recorded explicitly on a separate track as is done on many lower data rate systems. Packing density is so high (12,000 bits/cm/track = 30,000 bits/inch/track) that intertrack skew completely destroys the utility of an explicit clock track. Instead, the data clock is recovered by phase locking an oscillator to the transitions in the reproduced data. Each track has its own PLL to recover its clock. Next, the data stream is extracted from the PN sequence by a parity check scheme. The primitive polynomial used for the PN sequence in this machine is  $X^{17} + X^{14} + 1$ . Thus, the parity check network (mod 2 adder) takes three taps off a shift register containing the scrambled data. One consequence of this scheme is that all single bit errors that occur between the PN encoder and decoder will appear as three bit errors in the output data. In our preliminary testing we did observe that errors occurred in bursts of three.

The clock from one track (track 9 in this system) is arbitrarily assigned as the master clock and the final deskew operation uses this clock.

Due to skew problems, the 28 bits coming off the reproduce heads at any one instant are probably not the same 28 that were recorded simultaneously. Thus, a method is needed for realigning the data streams so that the 28 bits that went in simultaneously on record come back out simultaneously on playback. In order to do this, the synchronization characters inserted in the data stream on record must be recognized and sufficient buffer space must be provided to permit the system to wait for markers on all tracks before playing the data out without running out of buffer space first. Data block length must be large enough that the probability of slipping one whole block on any track with respect to the others is kept very small. Block length should be kept as small as possible to minimize deskew memory requirements.

Thus, blocks are 512 bits long (496 bits of data, 15 bits of synchronization character, 1 bit of parity) and 1K bits of memory are provided per track for deskew buffering. This system is capable of reproducing the input data smoothly and evenly with no gaps or discontinuities caused by having to wait for a late synch character. In earlier versions of the tape recorder the manufacturer experimented with shorter deskew buffers but found 1K to be best. Note that the particular value of block and buffer size are critically dependent on the skew characteristics of the tape transport.

## III. Error Rate Testing of the Data System

The first problem to be addressed after delivery of the system was the characterization of its overall error performance. The contractor's own testing was fairly low level and his test equipment did not have much resolution of error location. A significant problem in tape recording systems is the presence of bad spots on the tape. Bad spots contribute significantly to the overall error rate. The primary cause of bad spots is imperfections in the tape occurring during the manufacturing process. Other sources of bad spots or dropouts are fingerprints, dust and dirt, and so on. In order to distinguish errors due to bad spots on the tape from other errors, it is necessary to be able to identify a tape location very precisely.

Another major type of error source is the track dropout in which one particular data track makes a lot of errors (i.e., more than the average for normal tracks). Track dropouts can result from loss of lock by the PLL in the data electronics or from improper equalization of the filter in the low level amplifier section. The ability to identify errors on a track by track basis is another desirable feature in an error tester (Fig. 2).

Error testing with this system is a two-pass operation. On the first pass the tape is recorded. On the second pass the test

data is played back, compared with the original, and errors are counted.

The tester is interfaced to an SDS 930 computer through the Pin/Pot system. The computer can load or control all the internal registers as well as most of the control logic flip-flops. The user, through the computer, controls the configuration of the tester.

## A. Test Data Format

Two different types of data were selected for testing purposes: pseudo-noise sequence and DC. For the PN sequence data each track on the recorder receives a different phase of the same PN sequence. Eight different sequences are available ranging in length from  $2^{16} - 1$  to  $2^{23} - 1$  (i.e.,  $2^n - 1$ ,  $n = 16, 17, \dots, 23$ ).

The primitive polynomials used are:

$$X^{16} + X^5 + X^3 + X^2 + 1$$

$$X^{17} + X^3 + 1$$

$$X^{18} + X^7 + 1$$

$$X^{19} + X^6 + X^5 + X + 1$$

$$X^{20} + X^3 + 1$$

$$X^{21} + X^2 + 1$$

$$X^{22} + X + 1$$

$$X^{23} + X^5 + 1$$

For the DC data type each track receives a single bit from a 28-bit reference word which is loaded from the computer. Thus, except for synchronization characters inserted by the tester, the data on each track's input does not change.

Synchronization characters are inserted with both data types. The spacing between characters is determined by the PN sequence generator. Once each cycle of the PN sequence the sync character is inserted. The sync character contains block number information (a 16-bit number) so that longitudinal location on tape is determined by block number and bit number within the block. Figure 3 illustrates the test data formats.

The block number contained in a sync character is associated with the following data bits. Thus a location on tape is Block F, bit B, as in Fig. 4.

Note that the sync character used by the tester is completely unrelated to the sync information generated internally by the Sangamo data electronics. The Sangamo sync character is invisible to the user and there is no interaction with it.

The synchronization character is made up of three parts. Four tracks receive the parts of a 63-bit PN sequence broken into four 16-bit sections (with one extra bit added to make it 64). These four tracks are the synchronization tracks. Another seven tracks receive identical copies of the 16-bit block number. All the other tracks receive 16 one bits or 16 zero bits.

During playback/error count the tester searches for the sync character. The data from the synchronization tracks are cross-correlated with the 64 bits of the sync character. When the correlation coefficient is higher than a threshold which is controlled by the 930, the synchronization character is "detected." The block number acquired simultaneously is loaded into the block number register and an error count cycle is initiated. The block number is reconstructed by majority vote of the seven block number tracks.

During an error count cycle each reproduced bit is compared with the predicted bit for that location. Disagreements are accumulated in a register.

## B. Data Acquisition and Analysis

The next problems we had to address after designing and constructing the error tester described above were: What are some meaningful measurements of the system's performance? How do we go about making these measurements?

Some considerations that bore heavily on the decision-making process which answered those questions were:

- (1) The XDS 930 computer used to collect information from the error tester is much slower than the tester. Although the tester's resolution is 1 bit, the computer cannot examine the tester's registers fast enough to realize that resolution.
- (2) What resolution is meaningful and useful in evaluating the performance of the tape system? How large physically are the bad spots on tape and how far apart are they? Also, what good comes from knowing an error's location down to the nearest 0.76 micron (30 micro-inches) when the tape transport's position resolution is only 30 cm.
- (3) As we look closer and closer at the tape the amount of data we have to process grows. With a tape speed of

305 cm/s (120 ips) and a data rate of  $3.1 \times 10^6$  28-bit words per second the tester can produce  $3.1 \times 10^6$  5-bit numbers per second. Each 5-bit number is the total number of errors detected in one particular 28-bit word on tape. Thus, an error counting run of a 3300-meter reel of tape (a standard size) would produce  $3 \times 10^9$  5-bit words. To store all this information would require about  $1.5 \times 10^{10}$  bits of memory. Of course this error record would be very sparsely inhabited. If the actual error rate was close to the  $1.0 \times 10^{-5}$  specified for 305 cm/s (120 ips) operation, the table would only have about  $8 \times 10^5$  non-zero entries.

The physical length of a block of test data generated using the 16th-order polynomial is about 6.4 cm (2.5 in.). There are about 48,000 test data blocks in a 3300-meter reel of tape. We decided that tabulating errors on a block by block basis was a good compromise between computer memory limitations, transport position accuracy, and physical tape defect size. Since our early experiments indicated that even a block error count table would be quite sparse, we decided to note in the table only those blocks with non-zero error count. Thus, we discovered that 6000 memory locations were quite sufficient to hold error information generated from a 3300-meter tape (three locations per noted block).

Among the statistics we generated were:

- (1) Running overall bit error rate.
- (2) 100 frame boxcar – error rate over a 100-block-long “boxcar” which slides along.
- (3) 1000 block boxcar.
- (4) 300-meter boxcar.

We also generated two types of histograms:

- (1) A histogram in which bin #n contains the total number of blocks with n errors noted.
- (2) A histogram in which bin #n contains the number of times n errorless blocks occurred between two successive blocks containing errors.

## IV. Results and Conclusions

### A. Test Data and Error Performance

The results of our preliminary error testing of the tape system are enlightening and useful. The histogram in which bin #n contains the total number of blocks with n errors has

shown us the threefold multiplication of single bit errors which results from the PN decoding scheme used in the recorder/reproducer's playback electronics (Fig. 6).

The clear run histogram (bin #n contains the number of times exactly n blocks have passed between two successive error blocks) has exposed tape difficulties which produce low-frequency bursts of errors. This can result from a warped flange rubbing against the tape once each revolution of the reel. Figure 7 is one such histogram exhibiting a strong periodicity at about 17 blocks.

Multiple passes over one reel of tape have demonstrated our ability to locate bad spots on tape as we had hoped. Our results indicate that half of all errors are caused by these bad spots.

At 152 cm/s (60 ips) the overall bit error rate is about  $1.0 \times 10^{-6}$ . From tape to tape and from run to run it varies from as low as  $0.2 \times 10^{-6}$  to as high as  $10.0 \times 10^{-6}$ . Problems with tracking at 305 cm/s (120 ips) have prevented us from doing much work at this speed.

### B. Problems With the Electronics

Our main difficulties in getting the data electronics to perform reliably were the result of poor quality control in the construction of the electronic modules. The infant mortality rate for the data electronics system was extremely high. Between August of 1976 and March of 1977 we replaced at least 35 active components (realization of the importance of this statistic came late, so perhaps five or ten component replacements went undocumented) out of a total of 2450 active components in the data system. One particular transistor (2N4126) experienced 13 failures out of a total of 252 2N4126's in the system. During this time the data electronics were “burned in” for about 2100 hours.

Adjustment of the analog sections of the data electronics is complex and time consuming. The adjustments drift enough that equalization must be rechecked every three or four weeks. This drift may be caused by changes in the head characteristics due to wear.

### C. Problems With the Tape Transport

Of all the parts of this tape system the transport is probably the weakest. We had no trouble with the servo electronics, which performed well and reliably, but almost every other part of the transport gave us trouble.

Primary among the transport problems is the fact that the tape is not guided in any way. Neither the capstan nor any of the “guide” rollers provides any restoring force to keep the

tape centered on the tape path. Alignment of the tape path is extremely critical. If the tape on the reel is not precisely lined up with the tape path, the tape skews across the heads and the tape wraps very unevenly on the reel. This causes numerous dropouts as well as damage to the tape. This alignment problem is so severe that we are currently unable to record or playback at 305 cm/s (120 ips). The problem is less severe at 152 cm/s (60 ips) and we are able to use the recorder at this speed (and presumably below 152 cm/s (60 ips)).

Alignment of the tape path is extremely delicate and the construction of the adjusting screws does not lend itself to easy or reproducible changes.

The ability to align all the tape guide rollers parallel to the capstan is questionable because the aluminum plate on which all are mounted and to which all should be referenced (according to the factory) is not flat. Our measurements indicate that the surface deviates from flatness by 0.38 to 0.5 mm, though whether this is due to paint on the surface or to damage is not clear.

Overall it is clear that the transport is not up to the job of delivering the kind of performance required for this application.

#### **D. Ideas for the Future**

High-density digital tape recording has a lot of potential for future performance. This system as a whole is fairly well designed and, except for the transport, is certainly capable of meeting its specifications. More attention must be given in future efforts to the tape transport because a system of this type stands or falls by the transport's performance. A transport with vacuum column buffering and air bearing guides should show improved tracking over a tension arm/roller guide model such as this one.

To prevent the infant mortality problems we suffered an extensive burn-in is indicated. The manufacturer should emphasize control of component quality to prevent being stuck with a marginal quality production lot of components.

Despite the grim picture, we are obtaining satisfactory performance at 40 Mb/s and we may be able to get the full 80 Mb/s in the future by working on the transport alignment

problems. It should be possible in the future, given the knowledge we have acquired here, to procure a better system and get excellent performance.

#### **V. Data Buffer**

While the data rate of the tape system is quite high, the format is rigidly fixed. The two data rates available are about 40 Mb/s at a tape speed of 152 cm/s (60 ips) and 80 Mb/s at 305 cm/s (120 ips). In particular, the recorder will only accept 28 tracks of data at 3.1 MHz (305 cm/s = 120 ips) or 1.55 MHz (152 cm/s = 60 ips). If the user has, for example, 8 bits of data at 2 MHz something must be done to reformat the data. The first step toward a general-purpose buffer to interface any user to the tape system was taken with the construction of a special-purpose buffer for use in this year's Venus radar track (Fig. 5).

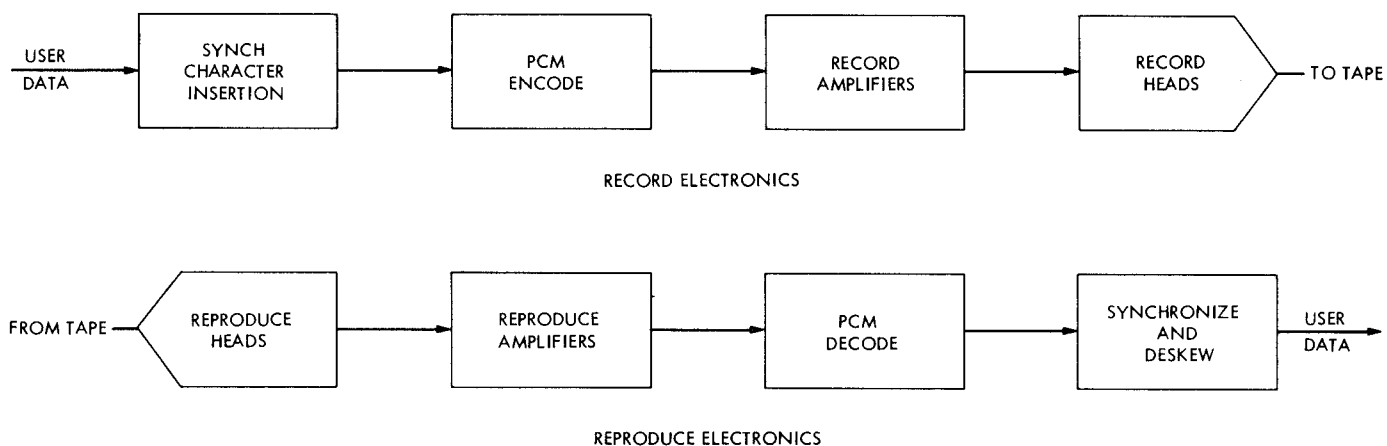
The Venus radar data was available as three synchronous 9-bit channels at about 800 kHz. We decided to run the recorder at 152 cm/s (60 ips) to minimize wasted capacity and because there were problems with the transport's tracking at 305 cm/s (120 ips).

The synchronizer (Fig. 5) gathers the three channels together and builds a 28-bit word for the tape system. The data channels are at the same frequency but exhibit a slight phase drift (about one cycle per day). Each channel is the digitized radar return from one of three stations.

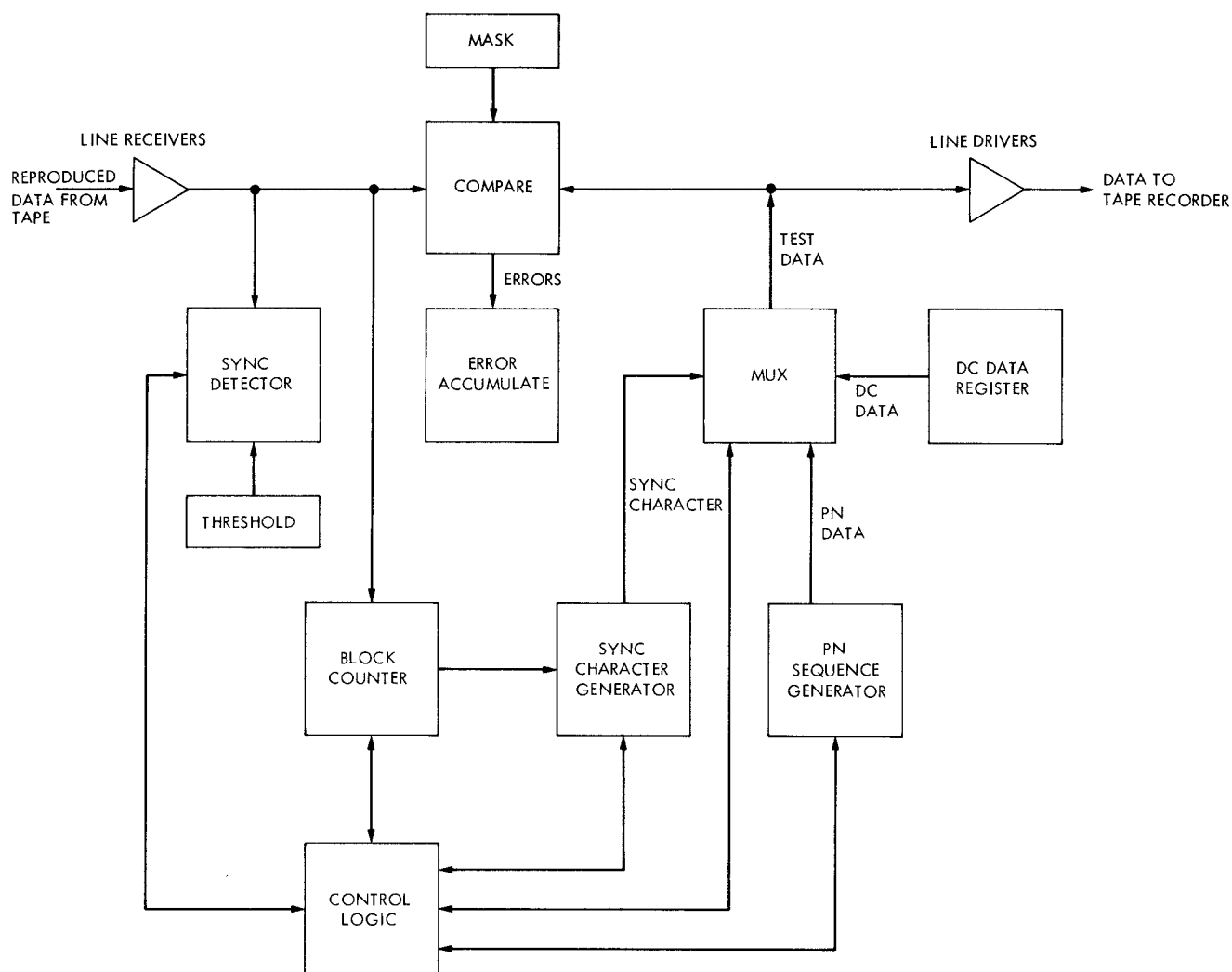
The memory is used to organize the data into 256 word blocks. The memory is organized as two banks of  $256 \times 28$  static RAM and they are commutated between read and write; while one is outputting to the tape, the other is accepting radar data. Each time a RAM bank is filled a block write is initiated. First, an 8-word synchronization character is written, followed by the 256 words of data.

In between blocks a square wave of half the frequency of the record clock is recorded. This minimizes the DC component of the data sent to the tape recorder. The system error rate of the tape recorder is very sensitive to any DC component of the input data, so this has proved necessary.

Detection of the sync character during playback is similar to that in the error rate tester.



**Fig. 1. Block diagram — HDR PCM system**



**Fig. 2. Error rate tester block diagram**

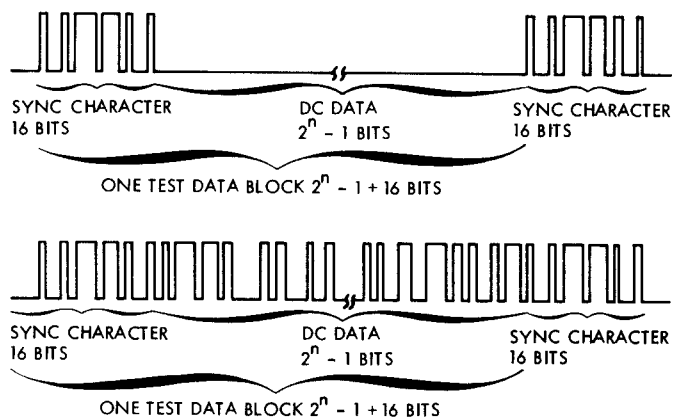


Fig. 3. Test data format

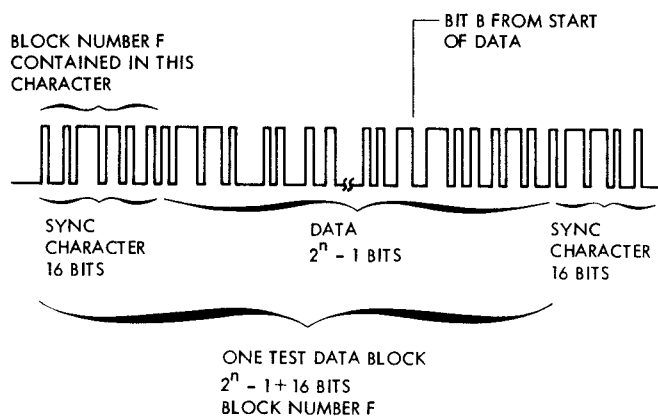


Fig. 4. Tape position addressing

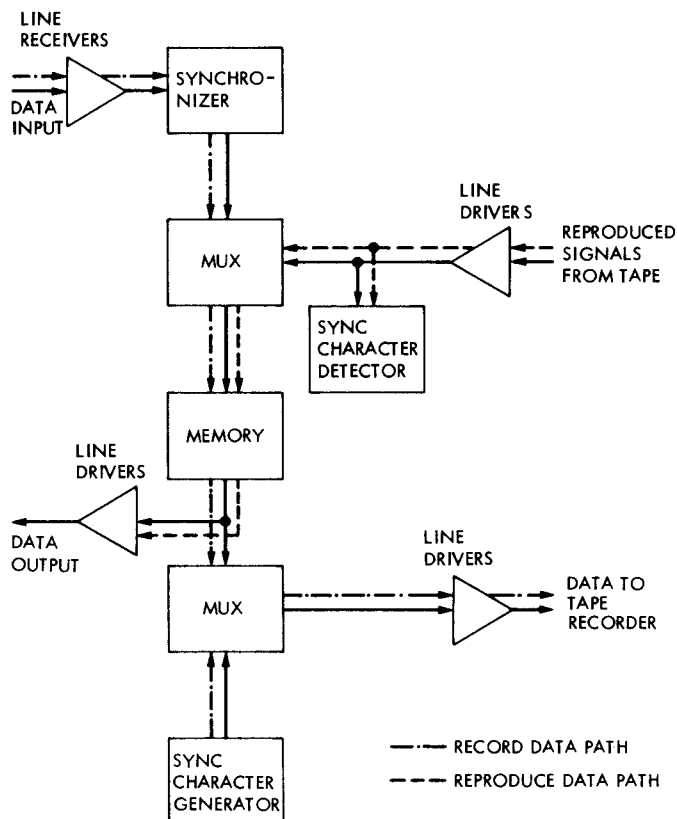


Fig. 5. Radar data buffer block diagram

# ERROR HISTOGRAM/1

0	1	2	3	4	5	6	7	8	9
4	1	2	65	5	4	34	5	2	19
8	0	15	3	0	12	9	2	4	2
3	3	2	3	3	2	1	6	0	1
2	4	1	1	0	1	0	2	1	5
4	0	2	1	1	0	0	4	2	1
1	2	3	1	3	4	4	3	0	0
0	2	3	3	1	2	2	1	0	2
1	0	1	1	0	2	2	1	0	1
0	1	2	5	4	2	0	1	1	3
4	1	0	0	1	0	1	2	3	0
2									

PEAK VALUE = 65 LINEAR SCALE

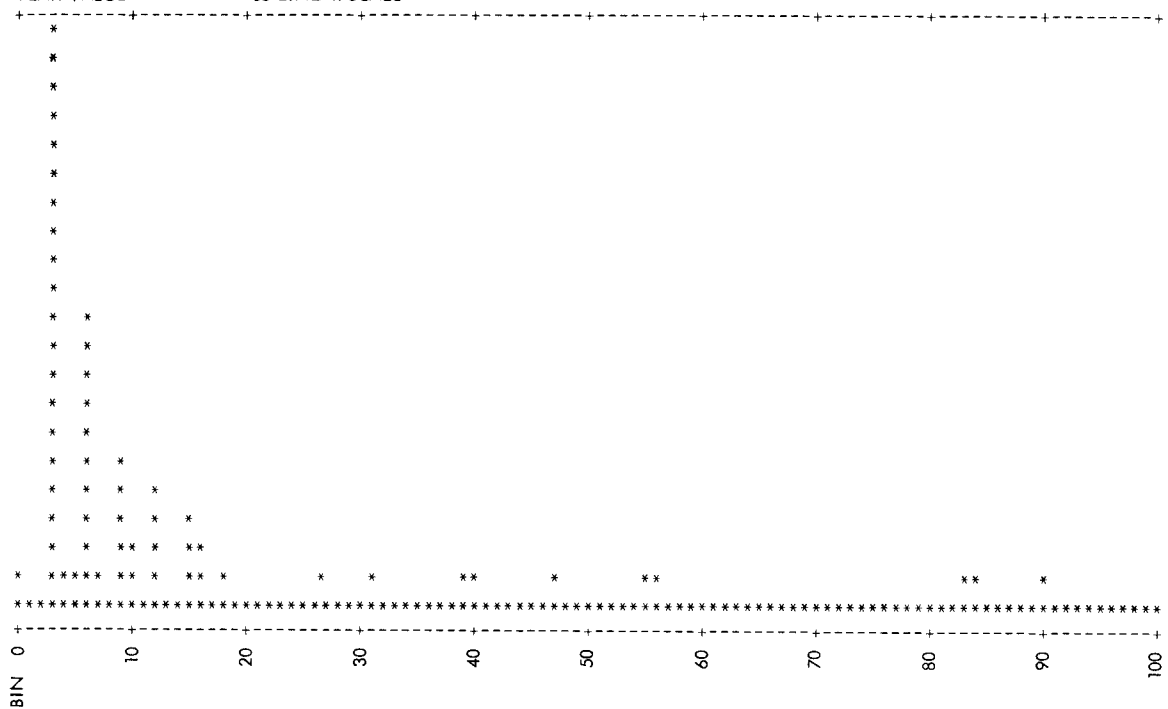


Fig. 6. Error histogram sample



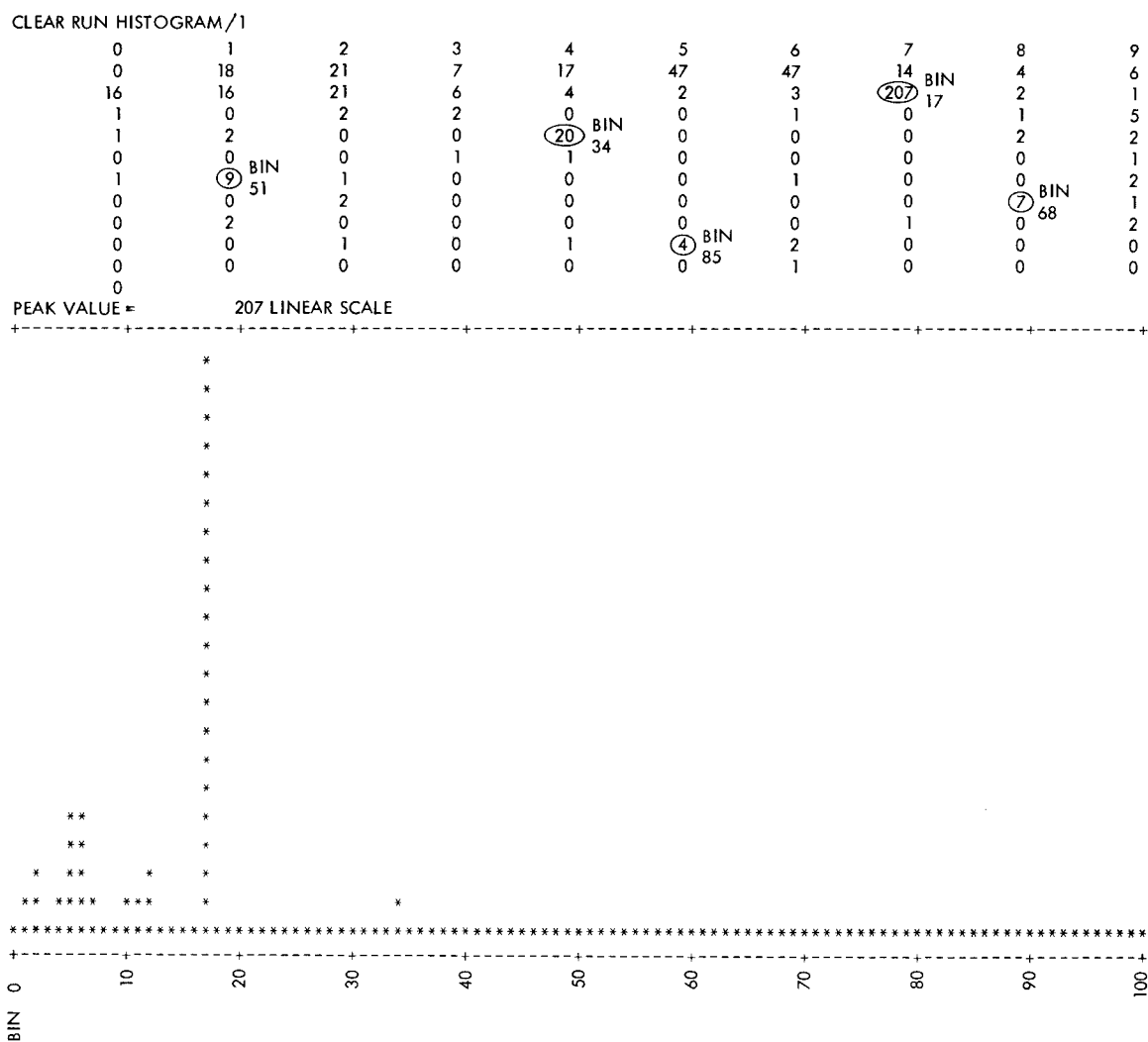


Fig. 7. Clear run histogram sample